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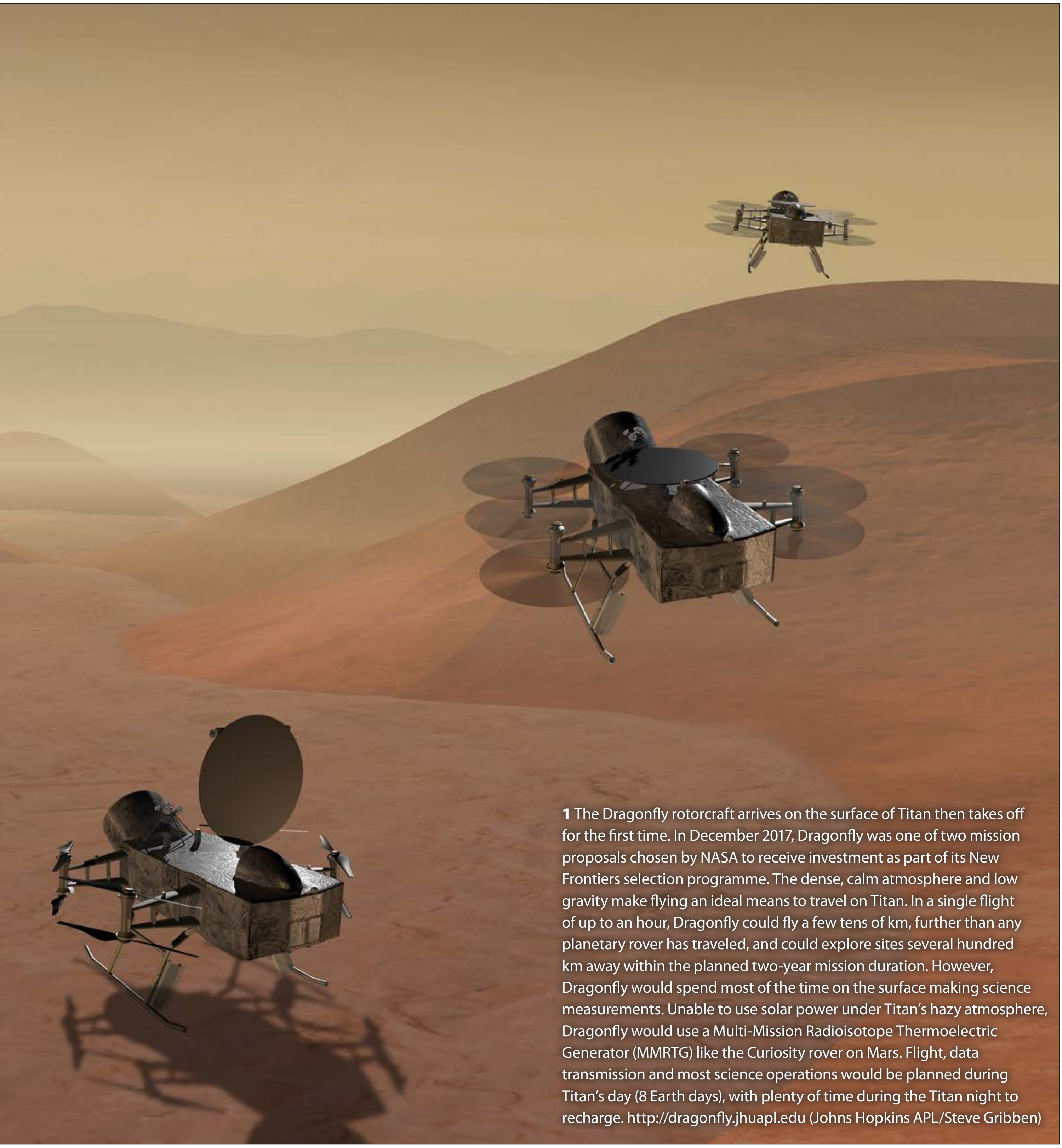
How to explore planets with drones

What could autonomous aircraft do for planetary exploration? **Sofie Macdonald** and **Adam Stevens** set out the potential and pitfalls of extraterrestrial drones.

The technology used to explore planetary surfaces has progressed rapidly from wire-guided squat rovers the size of a toy – the Mars 3 Prop-M rover, landed by the Soviet Union in 1971 but not deployed – to nuclear-powered rovers the size of cars, armed with an array of cutting-edge instruments – NASA's Mars Science Laboratory, currently exploring Gale Crater. Now, research is being carried out to design aerial vehicles able to function in the alien environments of our solar system. The Mars 2020 Rover may carry a scout helicopter (figure 4), while Dragonfly, a vertical-takeoff and landing (VTOL) vehicle designed to explore Saturn's moon Titan (Lorenz 2017), is one of two proposals in the final round of selection for NASA's New Frontiers programme (figure 1).

But why are drones so attractive for planetary exploration? To date, reconnaissance of planetary exploration sites has been achieved by orbital survey. An orbital platform can use cameras, altimeters and



1 The Dragonfly rotorcraft arrives on the surface of Titan then takes off for the first time. In December 2017, Dragonfly was one of two mission proposals chosen by NASA to receive investment as part of its New Frontiers selection programme. The dense, calm atmosphere and low gravity make flying an ideal means to travel on Titan. In a single flight of up to an hour, Dragonfly could fly a few tens of km, further than any planetary rover has traveled, and could explore sites several hundred km away within the planned two-year mission duration. However, Dragonfly would spend most of the time on the surface making science measurements. Unable to use solar power under Titan's hazy atmosphere, Dragonfly would use a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) like the Curiosity rover on Mars. Flight, data transmission and most science operations would be planned during Titan's day (8 Earth days), with plenty of time during the Titan night to recharge. http://dragonfly.jhuapl.edu (Johns Hopkins APL/Steve Gribben)

spectrometers to map the terrain and features of wide regions of a planet. Some say that we have a better understanding of the surface of Mars than the Earth's ocean due to the incredible work of orbiters such as Viking, Mars Global Survey, Mars Express, Mars Odyssey and MRO and their suites of instruments looking across the electromagnetic spectrum. Cutting-edge technology has driven resolution to the point where the Hi-Rise instrument on the Mars Reconnaissance Orbiter can image features as small as 25 cm (McEwen *et al.* 2007). On the other hand, Mars rovers now carry incredibly high-resolution instruments that can produce highly detailed surveys of the area around them and use advanced autonomous navigation systems to avoid obstacles without intervention from Earth. Yet a rock 24 cm across and invisible to an orbiter can cause a problem for a rover. Alternatively, it might be an ideal science target. The rover team won't know which until the rover travels close enough to find out, but rovers travel so slowly that it took Opportunity rover 14 years to cover 45 km. So much of planet Mars remains unexplored.

This is where drones or, more formally, unmanned aerial vehicles (UAVs), come in. UAVs can cover large areas relatively quickly and can collect samples from wider areas that would be impossible to reach with the limited mobility of rovers. Drone-based imaging systems would have greater resolution than orbiters and cover more ground than rovers, taking close-up images over wide distances. Their access to both the air and the ground makes it possible to sample a planet's atmosphere for analysis, while also scanning the surface composition, and do both at different places separated by greater distances than reachable by rover. UAVs are ideal to plug the gap between orbiters and rovers in our knowledge of other planets and could act in concert with another mission, as a scout for a rover in the Mars 2020 mission, for example, or as a standalone platform, as in the Dragonfly proposal.

The first, and so far only successful, planetary UAV mission was the Venus Vega balloons (figure 2). These two Soviet probes each carried a small balloon that was discharged into the atmosphere of Venus in 1985. Both balloons lasted only about two Earth days (Preston *et al.* 1986), providing data on wind speeds and the nature of atmospheric circulation at Venus. Since then, a wide range of aircraft have been proposed for incorporation into planetary missions. Proposals for Mars alone have included one-shot, disposable, drop from orbit, fixed-wing aircraft; trios of formation-flying gliders; lighter-than-air balloons or airships (Vargas *et al.* 1997); and several different VTOL rotorcraft (helicopters; Young *et al.* 2002). Similarly, a wide range of proposals have been made for missions to Venus and Titan, and even for missions to the gas giants, but none has made it beyond the concept stage.

"All vehicles would need to take off and land vertically, or stay aloft permanently"

Design

While the utility of aerial vehicles for planetary exploration might go without saying, designing such an aircraft to work on a different planet poses significant challenges. The most obvious factor that must be considered is the atmosphere. Here at the surface of Earth our atmosphere has a density of around $1.2\,\mathrm{kg\,m^{-3}}$ (varying with the weather), which imposes a pressure of roughly 101 kPa and is defined as 1 atmosphere (atm). This places a particular set of requirements on aircraft, which use wings, rotors or balloons to generate lift that can overcome gravity (see box "Aerofoils and balloons"). Many aircraft also use aerofoils for steering and propulsion.

However, 1 atm is not a constant across the solar system, or even in our own atmosphere, which becomes less dense with altitude. To operate under different atmospheric conditions, aircraft must be designed with the appropriate conditions in mind. The amount of lift, L, generated by an aerofoil can be calculated by

$$L = 0.5\rho v^2 S C_L \qquad (1)$$

where ρ is the atmospheric density, v is the airspeed, S is the wing area and C_L is the lift coefficient, which varies depending on the angle of the aerofoil, the Mach number (a measure of the airspeed relative to the speed of sound) and the Reynolds number (a measure of turbulence) (Anderson 2007). Equation 1 provides a good rule of thumb for designing aircraft, though of course it doesn't incorporate all the subtleties of aeronautical engineering. If we keep all things the same, but reduce the atmospheric density by half, then an aerofoil generates roughly half as much lift. Double the airspeed – quadruple the lift (though drag must also be taken into account). Double the wing area – double the lift (though structural rigidity becomes a concern). Aerofoils are designed with a particular set of conditions in mind. When an aeroplane is taking off or landing, it is moving significantly slower and through atmosphere at higher density than it experiences at its cruising altitude, which is why you can see the wing changing shape if you peer out of the window at the beginning or end of your flight.

On other planets, the environment is even more different from on Earth than the change between the Earth's surface and airline cruising altitude. At the surfaces of the three planetary bodies in the solar system with a substantial atmosphere, the atmosphere of Mars is approximately 100 times less dense (Leovy 2001), that of Titan approximately the same density as Earth (Mitchell & Lora 2016), and at Venus approximately 100 times more dense (Bullock & Grinspoon 1996). However, atmospheric density is not the only thing that changes – we must also take into account the gravitational attraction of the different bodies and balance this against any change in lift. Roughly speaking, Mars has a third of the gravity of Earth, Venus the same and Titan 10 times less. If we take this into account, an aircraft of similar design can carry around 30 times less mass on Mars, or would need to be 30 times more efficient or have a 30 times larger wingspan to carry the same mass; that design would carry 10 times more mass on Titan and 100 times more on Venus.

These factors provide a foundation for designing aircraft for use on other planetary bodies, but there are many others that must be considered. For example, given that there are currently no extraterrestrial runways, aircraft for all extraterrestrial bodies would need the ability to take off and land vertically, or to stay aloft permanently. Fixed-wing aircraft are not good at vertical take-off and landing, which means that proposals tend to be rotorcraft or hybrid vehicles with some fixed-wing and some vertical rotor elements. Using rotors for lift has the benefit of reducing the size of the vehicle, which cuts the need to "fold" any wings into a rocket aeroshell for transport from Earth; a possible disadvantage is that rotorcraft can carry less mass than a fixed-wing aircraft of the same size and require more power to stay aloft. Generally this means that potential aircraft for Mars would have severely limited payloads, but the high atmospheric density of Venus and low-gravity environment of Titan make them attractive targets for aerial vehicles.

2 The Russian Vega balloon mission to Venus, on display at the Udvar-Hazy museum. (G A Landis)

Control

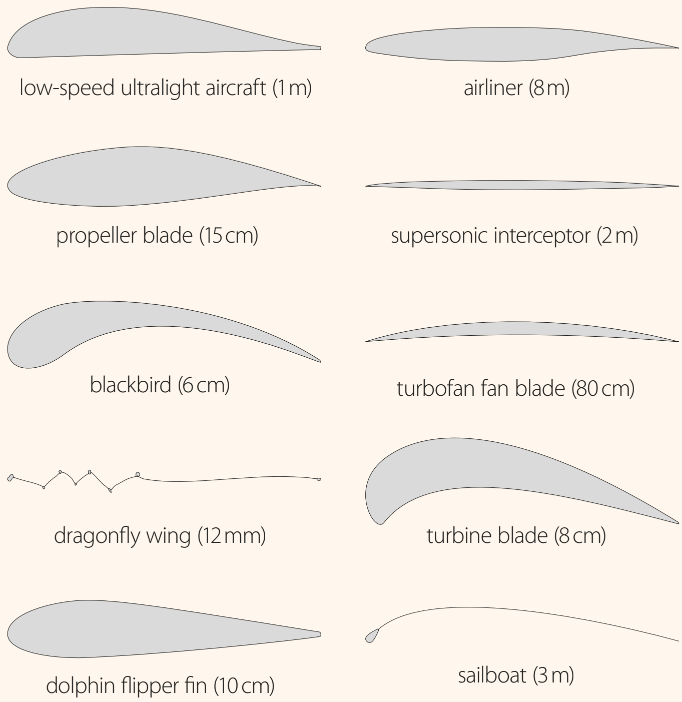
The intricacies of flight and the fast reaction times required to adapt to changing atmospheric conditions mean that aerial vehicles on other planets will need their own autonomous control systems. The vehicles will need to take off, navigate, take measurements and land with potentially pinpoint precision, all without direct control from Earth; communication delays make this impossible. While autonomous control systems are becoming commonplace here on Earth – you can buy drones boasting complex autonomous control on the high street – and rovers are incorporating more and more autonomous navigation (Bajracharya *et al.* 2008), flying around other planets presents a significantly bigger challenge. In particular, Mars, Venus and Titan all experience extensive storms that are considerably more unpredictable than those on Earth (Delitsky & Baines 2015, Schaller *et al.* 2009, Wang & Richardson 2015). Avoiding such storms would be imperative for any aerial vehicle.

Aerofoils and balloons

A wing-shaped body (aerofoil) moving through a fluid generates an aerodynamic force perpendicular to its motion. In the case of a wing, this force acts as lift, allowing a vehicle to fly. The lift produced by an aerofoil is almost "free", requiring only that the aerofoil is moving fast enough to generate more lift than the weight of the vehicle.

Helicopter rotors work in the same principle, with a number of "wings" rotating around a central point to lift the vehicle or, when tilted or rotated in particular ways, to thrust the vehicle forwards or steer it in a particular direction. Aircraft propellers work in the same way, but are generally devoted to providing thrust. Wings and rotors are both energy-efficient methods of flight compared to a rocket engine or similar, but rely on the atmosphere being dense enough to provide lift.

Balloons, on the other hand, provide lift using a compartment of gas that has a lower density than the atmosphere around it, making the entire vehicle buoyant. This can be achieved either by using a sealed container of gas with lower density than the atmosphere, such as hydrogen or helium, or by heating the ambient atmosphere inside a semi-closed container, such as in hot-air balloons. Montgolfière balloons, named for the inventor of the hot-air balloon, use passive solar heating, making them incredibly simple.



3 Examples of aerofoil profiles in Nature and in various vehicles.

Materials

Both Venus and Titan would also bring their own environmental challenges to the design of aircraft. Venus has a surface temperature of around 460 °C, high-speed winds, lightning and rain of concentrated sulphuric acid. Move away from the surface, where the temperature is lower, and you would end up flying through those same sulphuric acid clouds that were raining on you lower down. Titan is almost the opposite in some ways and similar in others, with a frigid surface at –180 °C, but also high-speed winds and potentially hazardous substances raining from a cloud layer. In this case though, the clouds and rain are formed of liquid hydrocarbons.

Extremes of temperature are a problem for electronics, especially when tied to mass limits for launch from Earth. In a hot environment, the electronics must be cooled, adding mass to your system. In a cold environment, the electronics must be warmed, adding mass to your system. Aircraft designed for Venus or Titan will need dedicated and powerful temperature control systems, but must also be built from materials that are capable of withstanding super-high or super-low temperatures (Landis 2006). Temperature-resistant materials are no mystery to spacecraft engineers, but normally these materials are required to withstand rapid changes in temperature, such as experienced during launch. Both Venus and Titan have effective heat distribution in their atmospheres, so that they maintain a fairly even temperature everywhere, but the stresses and strains associated with wings and rotors are unlike those faced by spacecraft outside an atmosphere: the materials must not be too brittle in the cold of Titan or too flexible in the heat of Venus, or the aerodynamic properties of the aircraft structure would be affected.

Aluminium and titanium are standard materials in the aerospace industry; they might not be the best choices for the extremes of Venus or Titan. Other alloys often employed for high-temperature uses in aerospace are based on nickel and iron, but these may one day be replaced by molybdenum or tungsten. Molybdenum is often used as a coating on the outer parts of spacecraft to shield less heat-tolerant materials against the extremely high temperatures generated during re-entry through the atmosphere. It has one of the highest melting points of all elements while being significantly lower density than other high-melting point metals. In addition, its very low coefficient of thermal expansion, as well as its high thermal conductivity, make it well suited for use in very-high-temperature environments. Beryllium copper and similar alloys are of interest to the aerospace industry because they possess high strength and hardness, excellent wear and fatigue resistance, and good corrosion resistance, as well as good thermal and electrical conductivities.

Carbon fibre materials are used in aerospace because of their low density but high strength and stiffness. However, some of their properties make them unsuitable for aircraft to fly on Venus or Titan. In particular, the standard resins used to fix carbon fibre materials are not resistant to heat, acid or hydrocarbon solvents and can simply melt or dissolve, losing structural support for the fibres. In addition, carbon fibres can be extremely brittle at the low temperatures encountered on Titan. The high concentration of sulphuric acid present throughout the atmosphere of Venus is a problem for several materials; even pure aluminium, which is typically resistant to corrosion, undergoes fairly extreme chemical reactions after long periods in concentrated sulphuric acid.

All of this suggests that when designing aircraft for extraterrestrial exploration, we can't just fall back on standard aerospace techniques and materials but should instead design with care for the specific environment that we aim to explore. Venus and Titan present extreme environments that will be a challenge for any engineer to design for, whereas Mars is slightly more benign, although the low atmospheric density means aircraft designs will need to be very efficient in order to carry any kind of useful payload.

Power

Power is a major issue for aerial vehicles. Solar power is not an option for aircraft under the thick haze of Venus or Titan; they would have to rely on radioisotope thermal generators (RTGs, described by O'Brien *et al.* 2008). These are relatively heavy,

"Solar power is not an option for aircraft under the thick haze of Venus or Titan"

reducing the mass available for the payload. They also give off a lot of waste heat. On Titan this waste heat could be used effectively to keep the rest of the aircraft warm, as is intended in the design for Dragonfly, but on Venus it would be a serious liability.

On Mars, an aircraft could use solar power, as a number of rovers have done, but to do so would require a reasonable surface area for solar panels. On a helicopter, there would be limits on space for solar panels but on a fixed-wing aircraft, the wings could feasibly be covered in solar panels. An aircraft for Mars could also use an RTG, but the martian atmosphere imposes strict limitations on aircraft mass – carrying an RTG would probably use up a majority of any available payload mass. Another limitation of solar power would be that, unless the power was managed exceptionally well, the aircraft would need to land at night. As the highest power requirements for any aircraft would be during take-off and landing, our Mars aircraft would need to charge for part of the morning, before taking off and using stored power to travel, leaving enough power to land safely. Such a schedule limits the amount of exploration possible.

There aren't many other power sources available for aerial exploration vehicles; one option would be to operate solely on batteries charged before arriving at the planet itself. This would limit the lifetime of the vehicle, perhaps only allowing it one flight – and such a mission would not really be exploiting the benefits of using an aerial vehicle in the first place. However, missions have been proposed with "fire-and-forget" aircraft, perhaps even launched from the upper atmosphere to allow them to glide long distances. There is also the option to use charging stations that stay in place on the surface of the planet (or are attached to a rover), but this would severely limit the range of an aircraft.

"A fleet of small aerial vehicles would offer advantages over a single larger one"

4 Artist's impression of the Mars Helicopter Scout. At the time of writing, trials were still being conducted and NASA had not decided whether the MHS will fly with the Mars 2020 mission. If it does, it will explore the terrain ahead of the rover, enabling it to drive up to three times futher each martian day. The helicopter would fly no more than three minutes per day and cover a distance of about 600 m. (NASA/JPL-Caltech)

Other vehicles

So far, we have only considered traditional aircraft that use rotors or fixed-wings. These make most effective use of an atmosphere for lift, but are not the only options. Science fiction has inpsired suggestions that the thick atmosphere and low gravity of Titan would allow humans to use wingsuits and flap like birds, providing enough power to stay aloft. This concept could be extended to unmanned vehicles (ornithopters) as well. Although technically feasible, it's not obvious what benefits such a design would have over fixed-wing or rotor vehicles.

Another technology that could be exploited is gas thrusters. These are used in aerial vehicles such as the Harrier Jump Jet and more modern F-35, where engine exhausts can be pointed downwards to provide lift. Similar techniques could be used in other planetary atmospheres, although this technique would be less efficient in the thin atmosphere of Mars. An extension of this technology would be to carry fuel for reaction mass, typically some kind of inert gas. This would allow thrusters to work more efficiently on Mars and even on airless bodies such as Europa, where aerial vehicles would otherwise be useful. However, the need to carry fuel would limit the lifetime of the vehicle and, as thrusters are not efficient, this would not be very long; this is why aircraft such as the Harrier rely on fixed-wing flight for long-distance travel.

We could also look back to earlier aerial exploration and exploit the relatively simple engineering of balloons. These avoid many of the drawbacks of fixed-wing and rotorcraft, although they would depend on reliable mechanisms for unfurling the balloon material after long periods of spaceflight. Balloons could carry compressed low-density gases such as hydrogen or helium to use in their envelopes, or use Montgolfière principles with heaters or passive solar heating. Propulsion could come from relatively small propellers, which would require little energy because there would be no requirement to move the vehicles as fast as a fixed-wing equivalent in order to stay aloft. Alternatively, balloons could be allowed to drift freely, measuring weather systems passively. A simple system would be a passively heated Montgolfière balloon with a small instrument package and no propulsion. Such a vehicle could easily collect data over large distances.

Finally, there is no reason to restrict ourselves to only one design for aerial vehicles. Aeronautical innovation on Earth has brought about any number of hybrid vehicles that exploit the benefits and reduce the drawbacks of any one type of design. The environments of other planetary bodies might lend themselves even more to hybrid aerial vehicles, so we might see any combination of fixed-wing, rotors, balloons and ornithopters in future. Nor do we need to restrict ourselves to a single vehicle. Just as there have been proposals for missions including multiple smaller components, a fleet of small aerial vehicles would offer advantages over a single larger one, though with the obvious restriction on the size of instruments. However, with on-going miniaturization across all types of instrumentation, this is becoming less of a problem.

Summary

With the prospect of two potentially interplanetary aerial vehicles in the near future, the world of extraterrestrial aerial design is an exciting one. The JPL-designed Mars Scout Helicopter could soon be acting as an autonomous pathfinder for the Mars 2020 rover, and we may see more detail of the surface of Titan than ever before via the Dragonfly rotorcraft if it continues through NASA mission selection. The fate of both vehicles will be decided over the coming weeks and years but, even if unsuccessful, advancements in aeronautical engineering on Earth make the prospects of aerial vehicles on other worlds that can map wider areas than rovers and in more detail than orbiters an obvious feature of the exploration of our solar system. ●

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